

**FHWA/IN/JTRP-2006/40**

**Final Report**

**IMPLEMENTATION OF HEALTH  
MONITORING PROCEDURES FOR  
ITS SENSORS**

***Volume 2: Implementation Report***

**Joseph M. Ernst  
Darcy M. Bullock**

**June 2008**



INDOT Research

# TECHNICAL *Summary*

Technology Transfer and Project Implementation Information

TRB Subject Code: 54-9 Traffic Control Device Procedures and Performance Measures  
Publication No.: FHWA/IN/JTRP-2006/40, SPR-3026

June 2008  
Final Report

## ***Implementation of Health Monitoring Procedures for ITS Sensors Volume 2: Implementation Report***

### **Introduction**

The Indiana Department of Transportation (INDOT) currently receives data from over 100 sensors strategically placed on Indiana's highways. Emphasis is being placed not only on the information being received, but also the quality of the information and of the sensors themselves. It is important to define quality metrics in order to implement numerical and standard ways of describing the quality of the sensor network. Turner [4] describes six aspects of sensor quality that should be considered: completeness, validity, timeliness, coverage and accessibility. Wells' project [2] continued work in this area by developing metrics.

The project described in this report aims to develop the tools necessary to quickly compute and access metrics that indicate the health of the sensors

and of the highway system itself. The INDOT system is a good environment for development of these tools. Their central database allows for easy access to data from sensors state wide.

Various metrics including volume of cars, average velocity, and standard deviation of velocity were computed at each site in 15 minute intervals. This data is available in the form of graphs that can be accessed from a webpage specifically designed for this purpose. The webpage includes a clickable google map interface with geocoded sensors, graphs of various metrics, text based reports, and the ability to download data in the form of text files. All graphs and webpages are automatically generated at the end of each day for analysis the following day.

### **Findings**

The web-based daily reports helped to monitor traffic flow throughout the INDOT system and to identify sites where the metrics indicated lowest quality data. Since the data is archived, improvements to the sensor network can be easily shown. During this project, construction was finished on many sites that were added to the sensor network. In addition, some sites that

were functioning poorly were recalibrated or repaired. These improvements to the system could be quickly verified each day by viewing the map display with the geocoded sensors. The metrics that have been discussed and developed have been shown to be useful tools in monitoring traffic sensor networks.

### **Implementation**

Based on the observations during this project, it would be advantageous for INDOT to continue development of the web-based, automatic sensor monitoring system. It may also

be useful to investigate other metrics and to continue implementing the remaining metrics developed by Wells.

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Final Report

FHWA/IN/JTRP-2006/40

**Implementation of Station Health Monitoring Procedures  
for ITS Sensors**

***Volume 2: Implementation Report***

by

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Joint Transportation Research Program  
Project No. C-36-75P  
File No. 8-9-16  
SPR-3026

Prepared in Cooperation with the  
Indiana Department of Transportation and the  
U.S. Department of Transportation  
Federal Highway Administration

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Indiana Department of Transportation or the Federal Highway Administration at the time of publication. This report does not constitute a standard, specification, or regulation.

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June 2008

|  |  |  |   |   |  |
|--|--|--|---|---|--|
| 1. Report No.<br>FHWA/IN/JTRP-2006/40-2  |  | 2. Government Accession No.                          |   | 3. Recipient's Catalog No.                                    |  |
| 4. Title and Subtitle<br>Implementation of Health Monitoring Procedures for ITS Sensors, Volume 2: Implementation Report   |  |  |   | 5. Report Date<br>June 2008                                   |  |
|  |  |  |   | 6. Performing Organization Code                               |  |
| 7. Author(s)<br>Joseph M. Ernst and Darcy M. Bullock   |  |  |   | 8. Performing Organization Report No.<br>FHWA/IN/JTRP-2006/40 |  |
| 9. Performing Organization Name and Address<br>Joint Transportation Research Program<br>School of Civil Engineering<br>Purdue University<br>West Lafayette, IN 47907-2051  |  |  |   | 10. Work Unit No.   |  |
|  |  |  |   | 11. Contract or Grant No.<br>SPR-3026                         |  |
| 12. Sponsoring Agency Name and Address<br>Indiana Department of Transportation<br>State Office Building<br>100 North Senate Avenue<br>Indianapolis, IN 46204   |  |  |   | 13. Type of Report and Period Covered<br>Final Report         |  |
|  |  |  |   | 14. Sponsoring Agency Code                                    |  |
| 15. Supplementary Notes<br>Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.   |  |  |   |   |  |
| <b>16. Abstract</b><br>Sensor health in distributed systems is a challenge found in every distributed sensor network. The sensor network that continues to be deployed by the Indiana Department of Transportation (INDOT) is an extremely distributed network that aims to eventually cover large portions of Indiana. It is important to develop quantitative and standardized metrics in order to quickly evaluate that status of the sensors in the network.<br><br>Previous works have described the importance of different aspects of sensor health and metrics for quantifying and standardization of these various aspects. This project worked towards the implementation of these metrics. This report will describe the web-based approach of summarizing the quality metrics. Care was taken to attempt to make the system user-friendly and as autonomous as possible. Colored balloons on geocoded Google maps attempt to quickly draw attention to areas with lower scores on the various quality metrics. This report attempts to describe the design decisions made during the development process. These will include the design of the website, quality metrics used, and how the quality metrics are displayed. |  |  |   |   |  |
| 17. Key Words<br>Sensor Data Quality, Sensors, Performance Metrics, Average Effective Vehicle Length, Sensor Co-Location   |  |  | 18. Distribution Statement<br>No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161 |   |  |
| 19. Security Classif. (of this report)<br>Unclassified   |  | 20. Security Classif. (of this page)<br>Unclassified |   | 21. No. of Pages<br>290                                       |  |
|  |  |  |   | 22. Price   |  |

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# 1 Background

ITS, intelligent transportation systems, are an important part of traffic engineering today. Wells [2] discusses the benefit of these sensor networks as a less expensive option to adding lanes. If existing lane capacity can be maintained with greater efficiency, then the need for lane construction will be decreased.

According to the Traffic Detector Handbook [1], millions of research dollars have been “applied to controlling traffic and alleviating congestion and delay...” The success of these control systems is greatly dependent on “the detector component of the overall system”.

As communication with traffic cabinets has become less expensive, it has become cost effective to collect information from sensors in a central database. The Indiana Department of Transportation (INDOT) currently collects data from over 100 sites. The INDOT database collects approximately 1,750,000 data points every day. Each data point includes many different metrics including the number of cars travelling through that site and their velocity.

Instead of making assumptions from scarce data, traffic engineers are now faced with finding the best way to interpret the constant flow of new data. The quality of the data received is very important. It is important to understand what kinds of quality metrics should be used. In Turner’s “Defining and Measuring Traffic Data Quality” [3] the following categories are recommended:

- Accuracy
- Completeness
- Validity



- Timeliness
- Coverage
- Accessibility

This report will focus on the importance of accessibility and its affect on the other five metrics. The timeliness of the data should be understood, not only as how fast the data can be collected, but also how quickly it can be retrieved and understood. Greater accessibility will also allow faster evaluation of the accuracy, completeness, and validity of the data.

This paper will recommend design specifications for a system that will monitor a state wide system of detectors. These recommendations are based on a prototype developed for the current INDOT database. The prototype was designed for two cities: Indianapolis and Gary. The primary goal of the prototype is to monitor sensor health in order to better allocate maintenance resources, but it will also provide traffic flow information.

## **2 High Level Design**

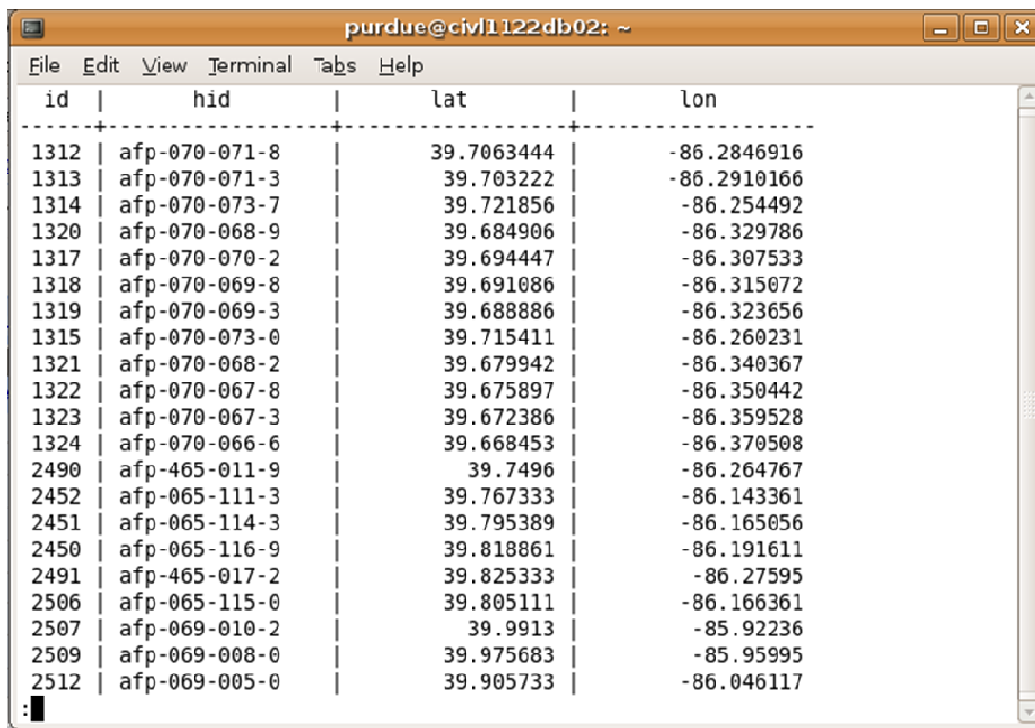
### ***2.1 Overview***

This section will discuss the motivation for the web based graphical design and the major components of the design. These will include the various ways to navigate the site and access information. The reports and graphs will be detailed in Chapter 3, Low Level Design.

### ***2.2 Motivation for web based graphical design***

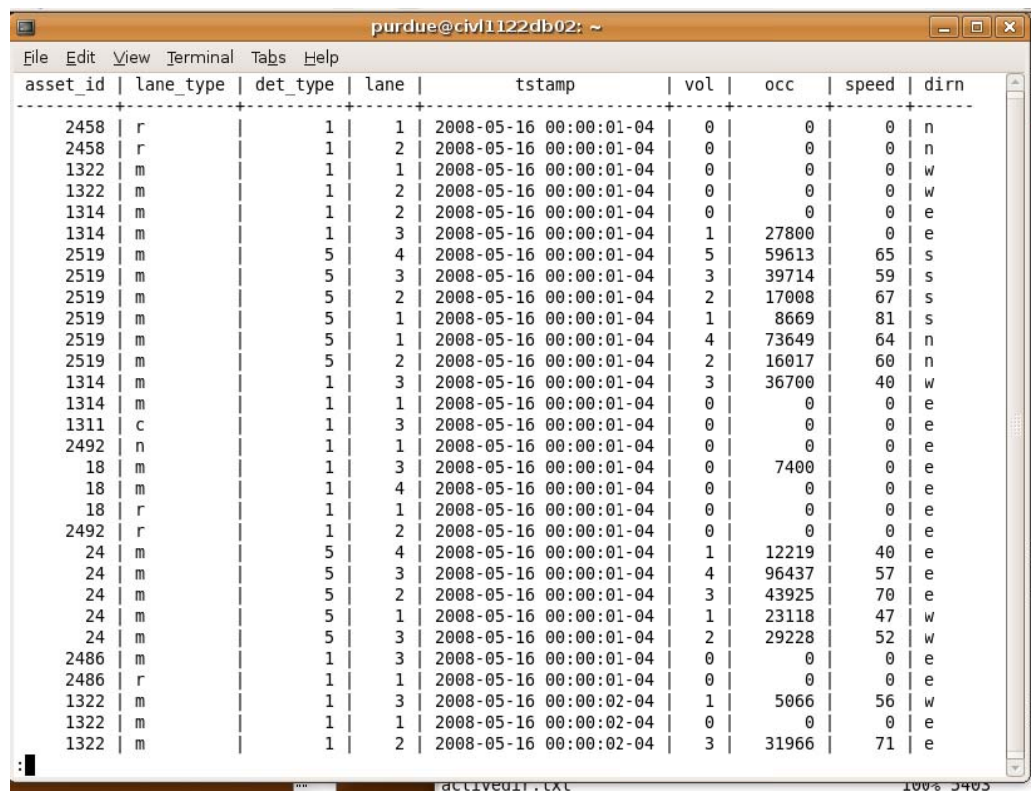
The amount of data collected at the central database can be overwhelming. There are approximately 1,750,000 rows added to the database every day from over 100 sites. These numbers continue to grow as more sites are added to the network. Figure 1 and Figure 2 show the raw data displayed by directly querying the database. It is difficult to gain a high level view of the system by viewing this raw data.

Figure 3 shows an example of how a Google Maps view of the system can be used to quickly show locations of interest by color coded balloons. By making these balloons clickable, traffic engineers can access the graphs more quickly.



| id   | hid           | lat        | lon         |
|------|---------------|------------|-------------|
| 1312 | afp-070-071-8 | 39.7063444 | -86.2846916 |
| 1313 | afp-070-071-3 | 39.703222  | -86.2910166 |
| 1314 | afp-070-073-7 | 39.721856  | -86.254492  |
| 1320 | afp-070-068-9 | 39.684906  | -86.329786  |
| 1317 | afp-070-070-2 | 39.694447  | -86.307533  |
| 1318 | afp-070-069-8 | 39.691086  | -86.315072  |
| 1319 | afp-070-069-3 | 39.688886  | -86.323656  |
| 1315 | afp-070-073-0 | 39.715411  | -86.260231  |
| 1321 | afp-070-068-2 | 39.679942  | -86.340367  |
| 1322 | afp-070-067-8 | 39.675897  | -86.350442  |
| 1323 | afp-070-067-3 | 39.672386  | -86.359528  |
| 1324 | afp-070-066-6 | 39.668453  | -86.370508  |
| 2490 | afp-465-011-9 | 39.7496    | -86.264767  |
| 2452 | afp-065-111-3 | 39.767333  | -86.143361  |
| 2451 | afp-065-114-3 | 39.795389  | -86.165056  |
| 2450 | afp-065-116-9 | 39.818861  | -86.191611  |
| 2491 | afp-465-017-2 | 39.825333  | -86.27595   |
| 2506 | afp-065-115-0 | 39.805111  | -86.166361  |
| 2507 | afp-069-010-2 | 39.9913    | -85.92236   |
| 2509 | afp-069-008-0 | 39.975683  | -85.95995   |
| 2512 | afp-069-005-0 | 39.905733  | -86.046117  |

Figure 1 Latitude and Longitude Database Output



| asset_id | lane_type | det_type | lane | timestamp              | vol | occ   | speed | dirn |
|----------|-----------|----------|------|------------------------|-----|-------|-------|------|
| 2458     | r         | 1        | 1    | 2008-05-16 00:00:01-04 | 0   | 0     | 0     | n    |
| 2458     | r         | 1        | 2    | 2008-05-16 00:00:01-04 | 0   | 0     | 0     | n    |
| 1322     | m         | 1        | 1    | 2008-05-16 00:00:01-04 | 0   | 0     | 0     | w    |
| 1322     | m         | 1        | 2    | 2008-05-16 00:00:01-04 | 0   | 0     | 0     | w    |
| 1314     | m         | 1        | 2    | 2008-05-16 00:00:01-04 | 0   | 0     | 0     | e    |
| 1314     | m         | 1        | 3    | 2008-05-16 00:00:01-04 | 1   | 27800 | 0     | e    |
| 2519     | m         | 5        | 4    | 2008-05-16 00:00:01-04 | 5   | 59613 | 65    | s    |
| 2519     | m         | 5        | 3    | 2008-05-16 00:00:01-04 | 3   | 39714 | 59    | s    |
| 2519     | m         | 5        | 2    | 2008-05-16 00:00:01-04 | 2   | 17008 | 67    | s    |
| 2519     | m         | 5        | 1    | 2008-05-16 00:00:01-04 | 1   | 8669  | 81    | s    |
| 2519     | m         | 5        | 1    | 2008-05-16 00:00:01-04 | 4   | 73649 | 64    | n    |
| 2519     | m         | 5        | 2    | 2008-05-16 00:00:01-04 | 2   | 16017 | 60    | n    |
| 1314     | m         | 1        | 3    | 2008-05-16 00:00:01-04 | 3   | 36700 | 40    | w    |
| 1314     | m         | 1        | 1    | 2008-05-16 00:00:01-04 | 0   | 0     | 0     | e    |
| 1311     | c         | 1        | 3    | 2008-05-16 00:00:01-04 | 0   | 0     | 0     | e    |
| 2492     | n         | 1        | 1    | 2008-05-16 00:00:01-04 | 0   | 0     | 0     | e    |
| 18       | m         | 1        | 3    | 2008-05-16 00:00:01-04 | 0   | 7400  | 0     | e    |
| 18       | m         | 1        | 4    | 2008-05-16 00:00:01-04 | 0   | 0     | 0     | e    |
| 18       | r         | 1        | 1    | 2008-05-16 00:00:01-04 | 0   | 0     | 0     | e    |
| 2492     | r         | 1        | 2    | 2008-05-16 00:00:01-04 | 0   | 0     | 0     | e    |
| 24       | m         | 5        | 4    | 2008-05-16 00:00:01-04 | 1   | 12219 | 40    | e    |
| 24       | m         | 5        | 3    | 2008-05-16 00:00:01-04 | 4   | 96437 | 57    | e    |
| 24       | m         | 5        | 2    | 2008-05-16 00:00:01-04 | 3   | 43925 | 70    | e    |
| 24       | m         | 5        | 1    | 2008-05-16 00:00:01-04 | 1   | 23118 | 47    | w    |
| 24       | m         | 5        | 3    | 2008-05-16 00:00:01-04 | 2   | 29228 | 52    | w    |
| 2486     | m         | 1        | 3    | 2008-05-16 00:00:01-04 | 0   | 0     | 0     | e    |
| 2486     | r         | 1        | 1    | 2008-05-16 00:00:01-04 | 0   | 0     | 0     | e    |
| 1322     | m         | 1        | 3    | 2008-05-16 00:00:02-04 | 1   | 5066  | 56    | w    |
| 1322     | m         | 1        | 1    | 2008-05-16 00:00:02-04 | 0   | 0     | 0     | e    |
| 1322     | m         | 1        | 2    | 2008-05-16 00:00:02-04 | 3   | 31966 | 71    | e    |

Figure 2 Volume, Occupancy and Speed Database Output

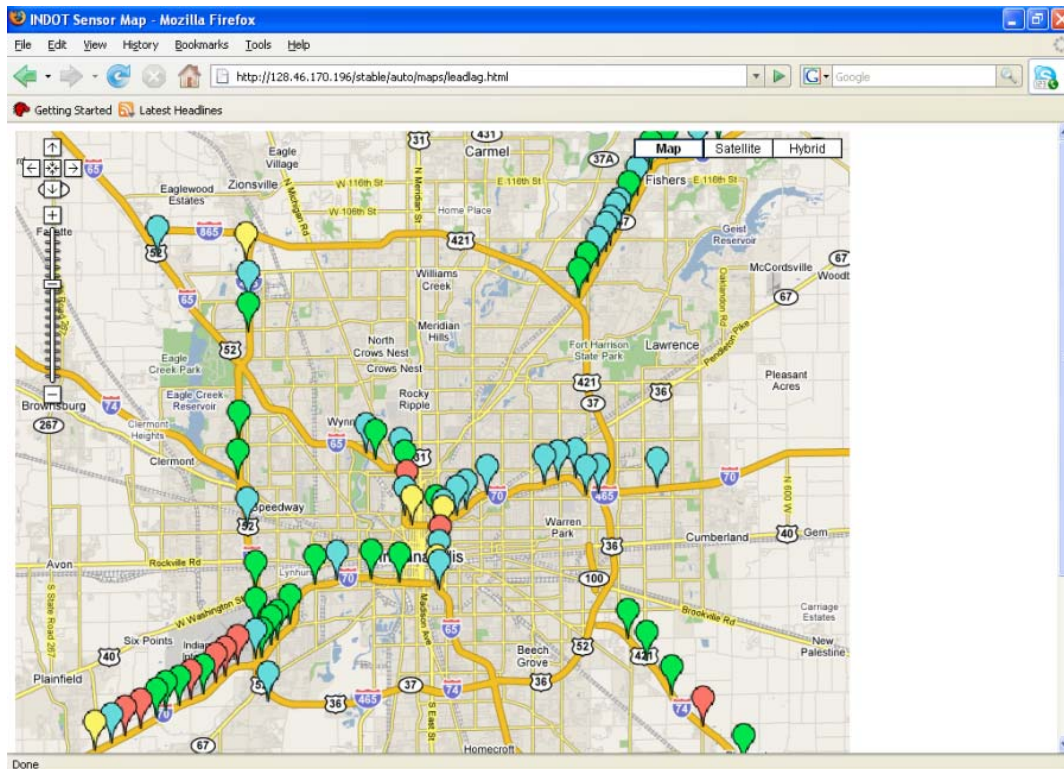


Figure 3 Example Geocoding in Google Maps

## ***2.3 Website design***

The website is designed for quick and easy navigation. Figure 4 shows the layout with the menu on the left that stays constant while the contents are displayed in the larger frame on the right. Figure 5 and Figure 6 show the options available in the menu.

There are four ways to get information from the website:

- 1) Map interface
- 2) Text Reports
- 3) CSV Files (Comma Separated Value Files)
- 4) URL lookup

Each of these options is useful for different types of diagnostics. The map interface is useful for finding a site by location and studying one site at a time. The Text Reports are good for looking at a specific metric on all sites throughout the system. The CSV files are good for exporting data, and the URL lookup is a good way to navigate the site without using the Google Maps Interface. Each of these will be discussed in the following sections.

Figure 4 Website Layout



Figure 5 Menu Layout (a)

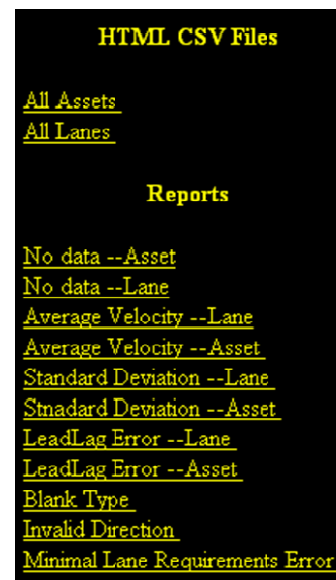


Figure 6 Menu Layout (b)

## **2.4 Map Interface**

The map interface reports are designed so that problems that would affect on entire site are listed first, then problems that severely affect a lane, and finally graphs that will allow an engineer to fine tune each lane. The information available by clicking the balloon varies depending on the map that is being viewed. The variations are shown in Figure 7, Figure 8, Figure 9, and Figure 10 and are described below.

The site level diagnostics are in a group called “NSEW Maps”. The “NSEW Maps” are:

- 1) NSEW map: details which directions are marked as active
- 2) NSEW rows map: details which sites are submitting data to the database

The other more specific diagnostic tools are in the “Error Maps” section. Each of these maps is available for the Indianapolis Site and the Gary Site. The first three maps in the “Error Maps” section all have the same information available by clicking the site balloons. The balloons for each map are color coded as described in Section 3.2 Google Maps Metrics.

The last map in the “Error Maps” section is the Report Error. It is different in that it only displays the configuration diagnostic information in the clickable balloons as shown in Figure 10. The balloons are colored red if there are questionable configurations and green if no questionable configurations are found.

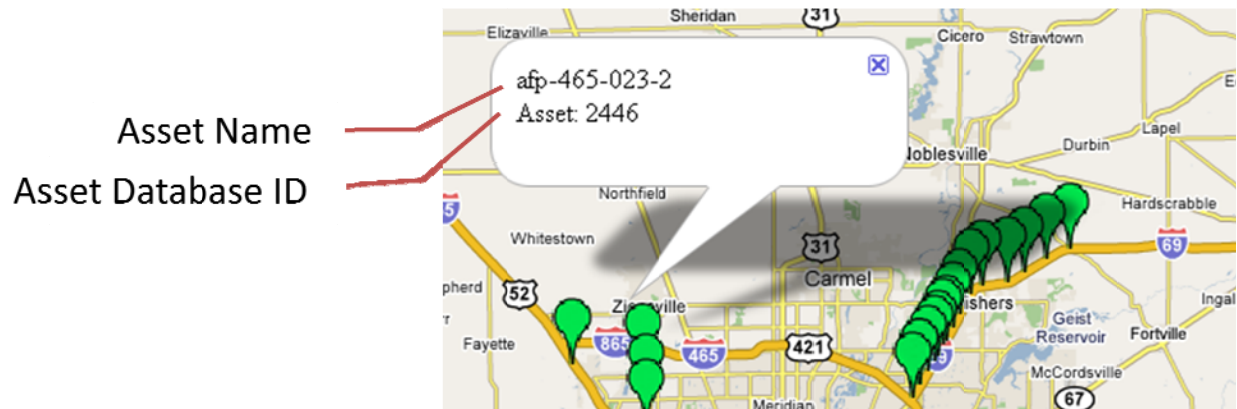


Figure 7 NSEW Balloon Description

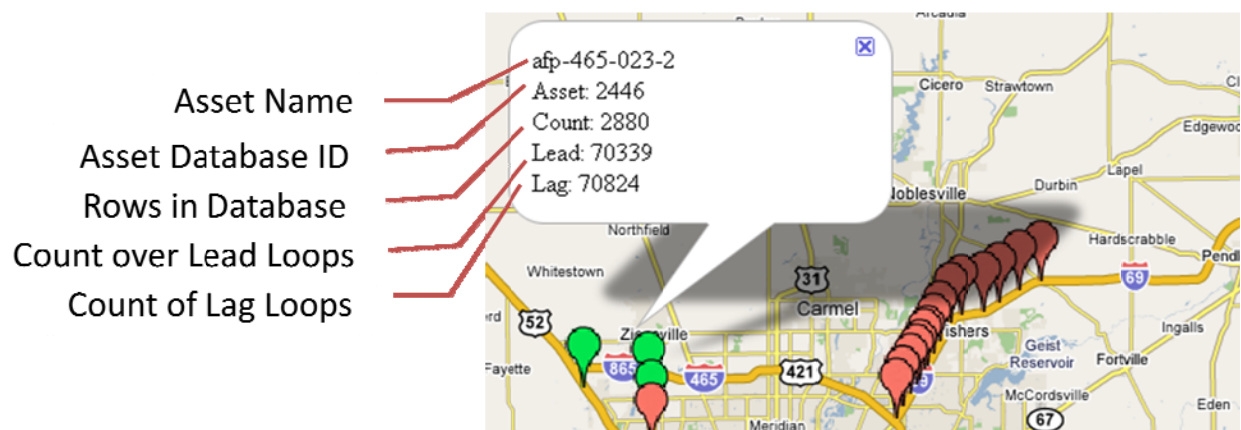


Figure 8 NSEW Rows Map Balloon



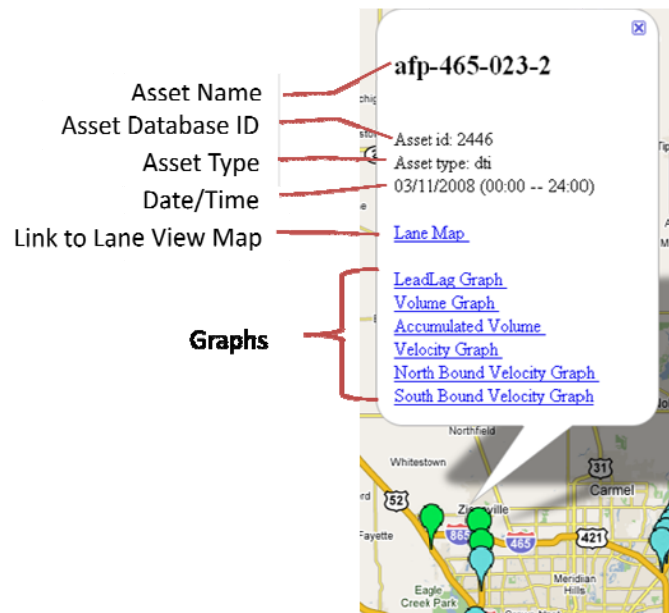


Figure 9 Error Maps Balloon

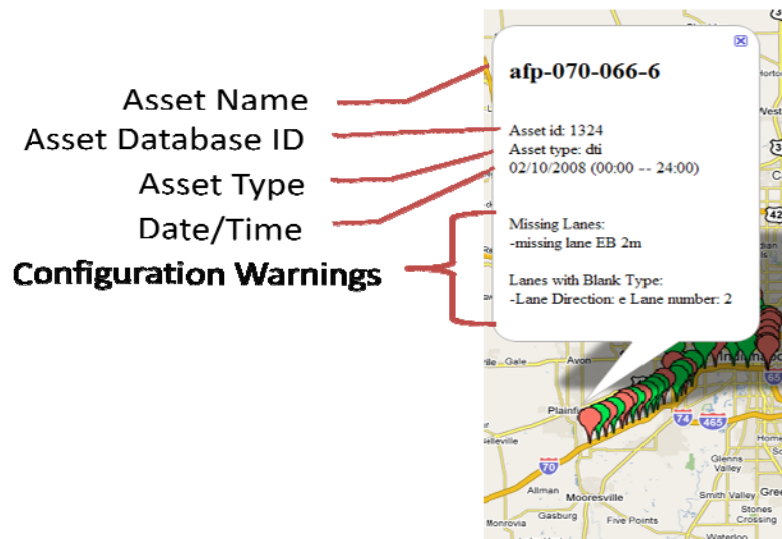


Figure 10 Configuration Error Maps Balloon

## 2.5 Text Reports

The “Reports” section is designed to focus on different aspects of a site or lane. There are reports that list possible configuration errors as well as reports that show the average velocity at each site or each lane. These reports are a quick way to get system wide information about a specific metric. The reports are detailed in section 3.3. They can be selected from the menu as shown in Figure 11.

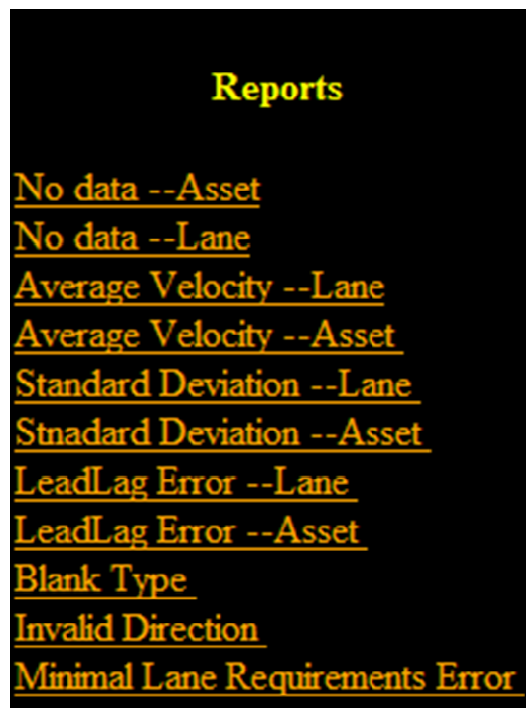


Figure 11 Text Reports

## 2.6 CSV Files

Comma separated files can be viewed and exported from the “HTML CSV Files” section. The “All Assets” section has data from the asset level analysis and the “All Lanes” section has data from the lane level analysis. These are convenient for exporting information to another program. They contain the values for each site/lane for each of the balloon coloring metrics.

**Table 1 Tables exported to Excel from the Comma Separated Files**

**a) Assets Table**

| Asset id | Type | Asset name    | n | s | e | w | lanes | kml lanes | count | lead   | lag    | avevel | stdvel |
|----------|------|---------------|---|---|---|---|-------|-----------|-------|--------|--------|--------|--------|
| 3        | dti  | afp-094-009-0 | 0 | 0 | 1 | 1 | 0     | 0         | 0     | 0      | 0      | -10    | -10    |
| 4        | dtm  | afp-094-008-2 | 0 | 0 | 1 | 1 | 0     | 0         | 0     | 0      | 0      | -10    | -10    |
| 5        | dtm  | afp-094-007-2 | 0 | 0 | 1 | 1 | 8     | 0         | 2871  | 0      | 0      | 71     | 20     |
| 6        | dti  | afp-094-006-4 | 0 | 0 | 1 | 1 | 10    | 0         | 5758  | 173916 | 178418 | 50     | 18     |
| 7        | dti  | afp-094-004-6 | 0 | 0 | 0 | 1 | 0     | 0         | 0     | 0      | 0      | -10    | -10    |
| 8        | dti  | afp-094-004-2 | 0 | 0 | 0 | 1 | 0     | 0         | 0     | 0      | 0      | -10    | -10    |
| 9        | dtm  | afp-094-003-8 | 0 | 0 | 1 | 1 | 8     | 0         | 2864  | 0      | 0      | 33     | 27     |
| 10       | dtm  | afp-094-002-9 | 0 | 0 | 1 | 1 | 8     | 0         | 2872  | 0      | 0      | 44     | 21     |
| 11       | dtm  | afp-094-001-2 | 0 | 0 | 1 | 1 | 8     | 0         | 2878  | 0      | 0      | 49     | 11     |
| 12       | dti  | afp-094-000-8 | 0 | 0 | 0 | 1 | 0     | 0         | 0     | 0      | 0      | -10    | -10    |
| 13       | dti  | afp-094-001-0 | 0 | 0 | 1 | 0 | 0     | 0         | 0     | 0      | 0      | -10    | -10    |
| 14       | dti  | afp-094-001-6 | 0 | 0 | 1 | 1 | 10    | 0         | 2879  | 179852 | 181097 | 70     | 19     |
| 16       | dti  | afp-094-002-5 | 0 | 0 | 1 | 1 | 10    | 0         | 5758  | 171609 | 171694 | 52     | 15     |
| 17       | dtm  | afp-094-002-8 | 0 | 0 | 1 | 1 | 8     | 0         | 2879  | 0      | 0      | 46     | 24     |

**b) Lanes Table**

| Asset id | Asset Name    | Lane num | Lane dir | Lane Type | count | lead  | lag   | error | average velocity |
|----------|---------------|----------|----------|-----------|-------|-------|-------|-------|------------------|
| 5        | afp-094-007-2 | 1        | e        | m         | 2715  | 0     | 0     | 0     | 52               |
| 5        | afp-094-007-2 | 2        | e        | m         | 2618  | 0     | 0     | 0     | 70               |
| 5        | afp-094-007-2 | 3        | e        | m         | 2824  | 0     | 0     | 0     | 64               |
| 5        | afp-094-007-2 | 4        | e        | m         | 2871  | 0     | 0     | 0     | 57               |
| 5        | afp-094-007-2 | 1        | w        | m         | 2330  | 0     | 0     | 0     | 71               |
| 5        | afp-094-007-2 | 2        | w        | m         | 2691  | 0     | 0     | 0     | 62               |
| 5        | afp-094-007-2 | 3        | w        | m         | 2793  | 0     | 0     | 0     | 50               |
| 5        | afp-094-007-2 | 4        | w        | m         | 2769  | 0     | 0     | 0     | 54               |
| 6        | afp-094-006-4 | 1        | e        | m         | 2879  | 19296 | 19416 | 6     | 63               |
| 6        | afp-094-006-4 | 2        | e        | m         | 2879  | 23305 | 23438 | 5     | 67               |
| 6        | afp-094-006-4 | 3        | e        | m         | 2879  | 21863 | 21890 | 1     | 60               |
| 6        | afp-094-006-4 | 4        | e        | m         | 2879  | 18824 | 18536 | 15    | 62               |
| 6        | afp-094-006-4 | 1        | e        | r         | 5758  | 4617  | 8897  | 481   | 63               |
| 6        | afp-094-006-4 | 1        | w        | m         | 2879  | 18717 | 18697 | 1     | 50               |
| 6        | afp-094-006-4 | 2        | w        | m         | 2879  | 19324 | 19647 | 16    | 61               |
| 6        | afp-094-006-4 | 3        | w        | m         | 2879  | 18034 | 18030 | 0     | 57               |
| 6        | afp-094-006-4 | 4        | w        | m         | 2879  | 20826 | 20797 | 1     | 57               |
| 6        | afp-094-006-4 | 1        | w        | r         | 2878  | 9110  | 9070  | 4     | 50               |
| 9        | afp-094-003-8 | 1        | e        | m         | 2584  | 0     | 0     | 0     | 60               |

## 2.7 URL Lookup

The graphs and maps are stored in a directory structure that is convenient to navigate without using the map interface. URLs to all graphs have the following structure:

WEBSITE/STATUS/archive/DATE/graphs/GRAPHNAME.png

- WEBSITE: The root website name
- STATUS: The website has a production copy named “stable” and a development copy named “unstable”
- DATE: The date in MM-DD-YYYY format
- GRAPHNAME: “asset” then the asset\_id from the database and then the graph type

This is particularly useful when wanting to compare two graphs. For example, the url for the Lead Lag Volume graph from the site on 465 at the 23.2 mile marker on May 29, 2008 is:

<http://128.46.170.196/stable/archive/05-29-2008/graphs/asset2446leadlag.png>

The date portion can then be changed to access the same graph from the previous day or the previous week. The graph from the previous week would be:

<http://128.46.170.196/stable/archive/05-22-2008/graphs/asset2446leadlag.png>

The possible graph types are detailed in section 3.4. They are listed below.

|          |  |
|----------|--|
| leadlag  | – lead and lag volume for each lane                            |
| lanevol  | – volume for each lane (where lead and lag data doesn't exist) |
| vel      | – average velocity vs. time for each direction                 |
| vele     | – velocity on each eastbound lane vs time                      |
| velw     | – velocity on each westbound lane vs time                      |
| veln     | – velocity on each northbound lane vs time                     |
| vels     | – velocity on each southbound lane vs time                     |
| vol      | – volume in each direction vs time                             |
| volaccum | – accumulated volume in each direction vs time                 |

## 3 Low Level Design

### 3.1 Overview

The low level design portion will give a detailed description of each of the reports available on the website. It will include the metrics used to color the balloons, the graphs, and the data found in text reports.

### 3.2 Google Maps Metrics

The maps are designed to allow the user to quickly evaluate the sensor network. Each of the maps focuses on different aspects of the data. The coloring for each map is noted below.

#### **NSEW Maps**

Green: North or South Directions are active

Red: East or West Directions are active

Blue: No directions are active

#### **NSEW Rows Maps:**

Green: Data is being entered into the database with non-zero values

Yellow: Data is being entered into the database but is all zero valued

Red: No data is being entered into the database from this asset

**LeadLag Error:**

Green: Lead and Lag Volumes differ by less than 10%

Yellow: Lead and Lag Volumes differ by between 10% and 20%

Red: Lead and Lag Volumes differ by more than 20%

Blue: Volumes are zero valued

**Ave Vel Error:**

Green: Average velocity is between 50 and 70 mph

Yellow: Average velocity is between 30 and 50 mph or between 70 and 100 mph

Red: Average velocity is more than 100 mph or less than 30 mph

Blue: Volumes are zero valued

**Std Vel Error:**

Green: Standard Deviation of velocity is less than 30 mph

Yellow: Standard Deviation of velocity is between 30 and 50 mph

Red: Standard Deviation of velocity is more than 50 mph

Blue: Volumes are zero valued

**Report Error:**

Green: There are no configuration warnings

Red: There are configuration warnings

### ***3.3 Text Based Reports***

The text based reports focus on different aspects of the sensor network. Each of these reports are described below and screenshots are shown in Figure 12 through Figure 29.

#### **No data –Asset (Figure 12)**

This report lists assets with no rows in the database. This could be caused by loose wires or errors in the configuration files

#### **No data –Lane (Figure 13)**

This report lists lanes which are adding rows to the database but all data is zero valued.

#### **Average Velocity Lane/Asset (Figure 14 and Figure 15)**

These reports list the average velocity of lanes or assets in descending order. This report is useful for finding assets and lanes that have impossible average velocities that may indicate a configuration error. This report can also be used to show sites that are congested and may need additional lanes.

#### **Standard Deviation Lane/Asset (Figure 16 and Figure 17)**

All lanes or assets listed in order from highest to lowest standard deviation of velocity. This is a good quality metric for the sensors. It is an indication of the noise level found at a lane or asset.



**LeadLag Error Lane/Asset (Figure 18 and Figure 19)**

The lead/lag errors takes the difference between the lead and lag volumes and divides by the maximum of the two. As a course metric it can be used to find lanes where the lead or lag sensor is not functioning. These will appear as 100% error. For the rest of the sites it can be an indication of the reliability of the sensors are and how well the lead and lag sensitivities are matched.

**Blank Type (Figure 20)**

Lanes must be designated as mainline (m), collector (c), or ramp(r). This is a list of all lanes that are not marked as any type.

**Invalid Direction (Figure 21)**

All lanes in the database should be marked with a direction. The valid options are North(N), South(S), East(E), or West(W). This is a list of all lanes that have another designation.

**Minimum Lane Requirements Error (Figure 22)**

All sites in the INDOT database are at least four lane highways. They should have at least 2 mainline lanes in each active direction. All mainline lanes that are missing are listed.

```

No Data Assets

Starttime:      2008-05-06 00:00:00
Endtime:        2008-05-06 24:00:00
-----
This report is a list of the asset which yeild no data
-----

afp-094-009-0
afp-070-086-4
afp-070-084-9
afp-070-083-9
afp-070-083-6
afp-070-088-0
afp-070-089-2
afp-070-087-0
afp-070-087-5
afp-070-088-7
afp-065-254-0
afp-465-009-5
afp-465-008-2
afp-465-016-0
afp-069-004-4
afp-069-003-2
afp-069-002-9
afp-069-002-4
afp-069-002-1
afp-069-001-5

```

Figure 12 Asset Report: No Data

```

No Data Lanes

Starttime:      2008-05-06 00:00:00
Endtime:        2008-05-06 24:00:00
-----
This report is a list of the lanes which yeild no data
-----

afp-070-073-0 e1m
afp-069-000-9 s4m
afp-069-000-9 s3m
afp-069-000-9 s2m
afp-069-000-9 s1m
afp-069-000-9 n4m
afp-069-000-9 n3m
afp-069-000-9 n2m
afp-069-000-9 n1m
afp-069-000-5 s4m
afp-069-000-5 s3m
afp-069-000-5 s2m
afp-069-000-5 s1m
afp-069-000-5 n4m
afp-069-000-5 n3m

```

Figure 13 Lane Report: No Data

```

Average velocities per lane

Starttime:      2008-05-06 00:00:00
Endtime:        2008-05-06 24:00:00
-----
This report is a descending list of the average
velocity of the lane
-----

Asset           |      Average Velocity (mph)
afp-465-021-2 s4m |      145
afp-065-116-9 s2m |      135
afp-074-095-0 w2m |      132
afp-070-076-6 e2m |      130
afp-065-256-3 s2m |      129
afp-465-021-2 s2m |      125
afp-070-068-9 w2m |      114
afp-074-097-6 w2m |      111
afp-465-023-2 n2m |      111
afp-065-116-5 n2m |      110
afp-070-067-8 s2m |      108

```

Figure 14 Lane Report: Average Velocity

```

Average velocities per asset

Starttime:      2008-05-06 00:00:00
Endtime:        2008-05-06 24:00:00
-----
This report is a descending list of the average
velocity of the lane at the asset that is furthest from 60 mph
-----

Asset           |      Average Velocity (mph)
afp-465-021-2   |      145
afp-065-116-9   |      135
afp-074-095-0   |      132
afp-070-076-6   |      130
afp-065-256-3   |      129
afp-070-068-9   |      114
afp-074-097-6   |      111
afp-065-116-5   |      110
afp-070-067-8   |      108
afp-070-068-2   |      104
afp-070-079-5   |      102
afp-065-111-9   |      100
afp-094-007-6   |       97
afp-074-099-0   |       95
afp-070-074-1   |       94

```

Figure 15 Asset Report: Average Velocity

```

Standard deviation of velocities per lane

Starttime:      2008-05-06 00:00:00
Endtime:        2008-05-06 24:00:00
-----
This report is a descending list of the standard deviations
or the velocity of each lane
-----

Asset           |      Standard Deviation of Velocity (mph)
afp-465-023-2 n2m |      110
afp-465-021-2 n2m |      104
afp-070-078-6 w2m |      100
afp-070-076-6 e3m |       95
afp-065-116-9 n1m |       95
afp-065-256-3 n1m |       86
afp-070-076-6 w1m |       85
afp-465-021-2 n1m |       84
afp-070-071-8 w1c |       84
afp-070-071-8 w1m |       84
afp-465-021-2 n4m |       83
afp-065-116-9 s3m |       82
afp-070-079-5 w4r |       78
afp-465-021-2 s1m |       77

```

Figure 16 Lane Report: Standard Deviation of Velocity

```

Standard deviation of velocities per asset

Starttime:      2008-05-06 00:00:00
Endtime:        2008-05-06 24:00:00
-----
This report is a descending list of the average
the standard deviation of the worst lane is displayed
-----

Asset           |      Standard Deviation of Velocity (mph)
afp-465-023-2   |      110
afp-465-021-2   |      104
afp-070-078-6   |      100
afp-070-076-6   |       95
afp-065-116-9   |       95
afp-065-256-3   |       86
afp-070-071-8   |       84
afp-070-079-5   |       78
afp-065-116-5   |       72
afp-070-067-8   |       71
afp-070-068-2   |       68
afp-070-074-7   |       65
afp-074-095-0   |       61
afp-065-111-9   |       60
afp-070-074-1   |       58
afp-070-068-9   |       57
afp-070-070-2   |       56
afp-070-071-3   |       54
afp-070-072-3   |       54
afp-070-070-7   |       53
afp-070-073-7   |       51

```

Figure 17 Asset Report: Standard Deviation of Velocity

Lead Lag Volume Discrepancies per lane

Starttime: 2008-05-06 00:00:00  
Endtime: 2008-05-06 24:00:00

-----

This report is a descending list of the percentage of error between the lead volume and lag volume  
The absolute difference between lead and lag volumes is also displayed

Percentage error =  $\text{abs}(\text{lead}-\text{lag})/\text{max}(\text{lead},\text{lag})$  for each lane  
Absolute difference =  $\text{abs}(\text{lead}-\text{lag})$

-----

| Lane              | Percentage Error | Absolute Difference (counts) |
|-------------------|------------------|------------------------------|
| afp-070-071-8 e3m | 100.0%           | 9237                         |
| afp-074-099-0 w2m | 100.0%           | 11489                        |
| afp-065-111-3 s3m | 100.0%           | 9309                         |
| afp-065-111-3 s2m | 100.0%           | 20412                        |
| afp-065-111-3 n3m | 100.0%           | 20319                        |
| afp-065-111-3 ?2  | 100.0%           | 5579                         |
| afp-065-114-3 s1m | 100.0%           | 2651                         |
| afp-070-068-2 e3m | 100.0%           | 12383                        |
| afp-070-078-6 e2m | 95.8%            | 19200                        |
| afp-065-111-3 n4m | 92.3%            | 16327                        |
| afp-070-072-3 w3c | 78.6%            | 151                          |
| afp-070-071-3 e3m | 46.2%            | 3351                         |
| afp-070-071-8 w3c | 44.5%            | 33                           |
| afp-070-070-2 e1c | 37.5%            | 9                            |
| afp-070-070-2 e4  | 34.4%            | 10                           |

Figure 18 Lane Report: Lead/Lag Volumes

Lead Lag Volume Discrepancies per asset

Starttime: 2008-05-06 00:00:00  
Endtime: 2008-05-06 24:00:00

-----

This report is a descending list of the percentage of error between the lead volume and lag volume  
The absolute difference between lead and lag volumes is also displayed

Percentage error =  $\text{abs}(\text{lead}-\text{lag})/\text{max}(\text{lead},\text{lag})$  for each lane then maximum lane is chosen  
Absolute difference =  $\text{abs}(\text{sum}(\text{lead of each lane})-\text{sum}(\text{lag of each lane}))$

-----

| Asset         | Percentage Error | Absolute Difference (counts) |
|---------------|------------------|------------------------------|
| afp-070-071-8 | 100.0%           | 10147                        |
| afp-074-099-0 | 100.0%           | 11301                        |
| afp-065-111-3 | 100.0%           | 8569                         |
| afp-065-114-3 | 100.0%           | 2651                         |
| afp-070-068-2 | 100.0%           | 11674                        |
| afp-070-078-6 | 95.8%            | 20310                        |
| afp-070-072-3 | 78.6%            | 1065                         |
| afp-070-071-3 | 46.2%            | 4907                         |
| afp-070-070-2 | 37.5%            | 4135                         |
| afp-065-110-3 | 20.4%            | 2664                         |
| afp-065-111-9 | 16.8%            | 662                          |
| afp-065-256-3 | 15.6%            | 1489                         |
| afp-094-007-6 | 15.2%            | 626                          |
| afp-065-113-1 | 14.1%            | 976                          |
| afp-070-066-6 | 11.1%            | 81                           |

Figure 19 Asset Report: Lead/Lag Volumes

```

Asset name: afp-070-070-2      Asset 1317:
-Lane Direction: e    Lane number: 4

Asset name: afp-070-068-9      Asset 1320:
-Lane Direction: ?    Lane number: 1
-Lane Direction: ?    Lane number: 2

Asset name: afp-065-111-3      Asset 2452:
-Lane Direction: ?    Lane number: 2

```

**Figure 20 Blank Type Report**

```

afp-070-068-9    Asset id: 1320
-Lane number: 1 Lane direction:?
-Lane number: 2 Lane direction:?

afp-065-111-3    Asset id: 2452
-Lane number: 2 Lane direction:?

```

**Figure 21 Invalid Direction Report**

```

Asset name: afp-094-009-0      Asset id:3
-missing lane EB 1m
-missing lane EB 2m
-missing lane WB 1m
-missing lane WB 2m

Asset name: afp-094-008-2      Asset id:4
-missing lane EB 1m
-missing lane EB 2m
-missing lane WB 1m
-missing lane WB 2m

Asset name: afp-094-007-2      Asset id:5
-missing lane EB 1m
-missing lane EB 2m
-missing lane WB 1m
-missing lane WB 2m

Asset name: afp-094-006-4      Asset id:6
-missing lane EB 1m
-missing lane EB 2m
-missing lane WB 1m
-missing lane WB 2m

```

**Figure 22 Minimum Lane Requirements Error Report**

### 3.4 *Graphs*

This section will detail the various graphs that are automatically generated every day. These can all be accessed through the hyperlinks on the google maps page, or by directly entering the URL as described in section 2.7.

The possible graph types are

|          |  |
|----------|--|
| leadlag  | – lead and lag volume for each lane                            |
| lanevol  | – volume for each lane (where lead and lag data doesn't exist) |
| vel      | – average velocity vs. time for each direction                 |
| vele     | – velocity on each eastbound lane vs time                      |
| velw     | – velocity on each westbound lane vs time                      |
| veln     | – velocity on each northbound lane vs time                     |
| vels     | – velocity on each southbound lane vs time                     |
| vol      | – volume in each direction vs time                             |
| volaccum | – accumulated volume in each direction vs time                 |

### 3.4.1 Lead Lag Graph

The lead lag graph can be helpful to identify lanes where the lead and lag sensor sensitivity are not well matched. An example is shown in Figure 23. This graph quickly shows that Southbound Lane 1 is not as well matched as the rest of the lanes.

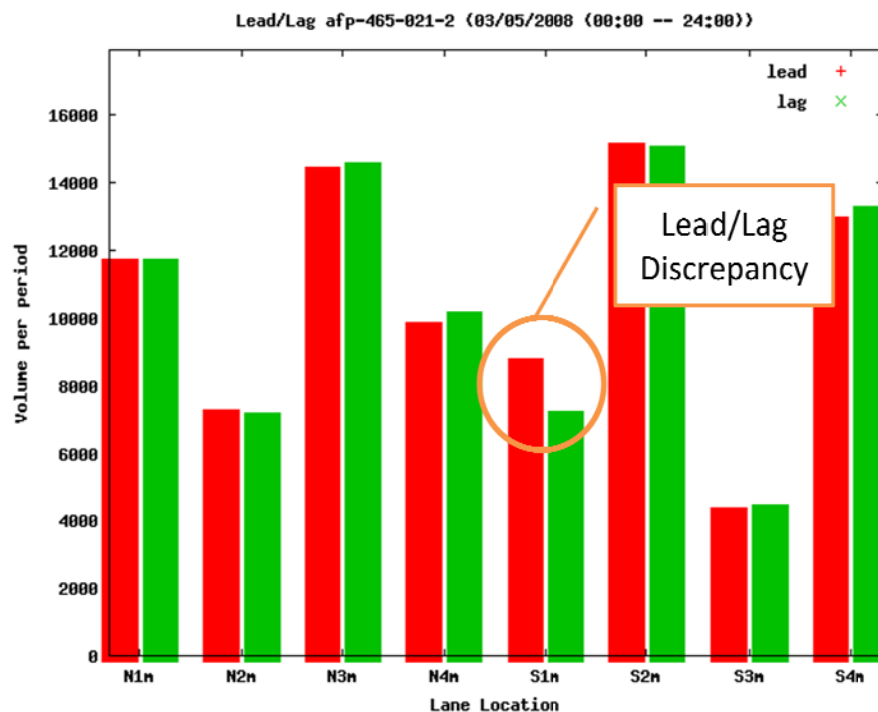


Figure 23 Lead/Lag Example Graph

### 3.4.2 Lanevol (Lane Volume)

The lanevol graph shows the volume of cars for that day at each lane. This does not have the redundant data that allows us to double check the accuracy of the sensors, but is the closest available information to the Lead Lag graph at sites where only one volume estimate is available.



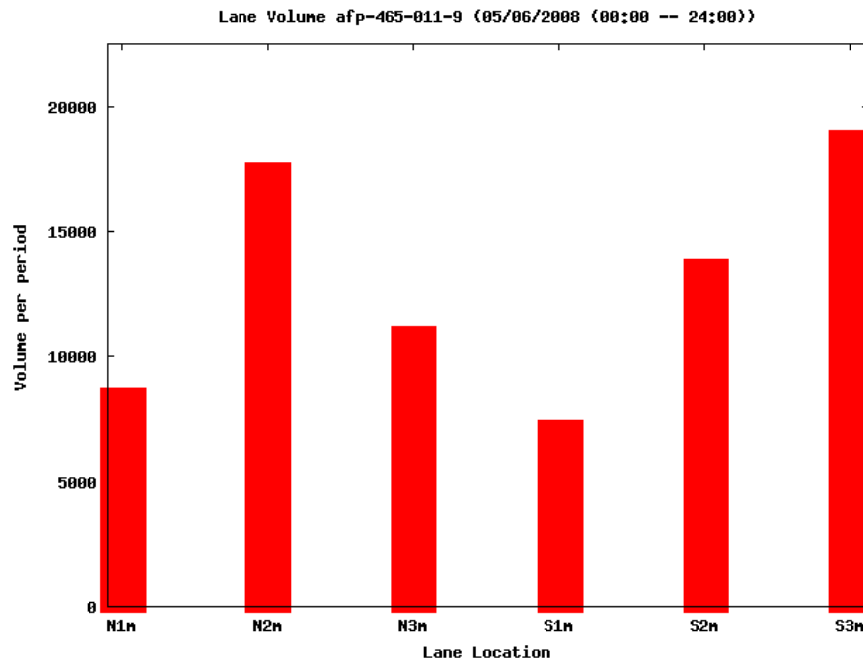


Figure 24 Lane Volume Example Graph

### 3.4.3 Velocity (vel)

This graph shows the average velocity in each direction. This is useful for finding what time of day is most congested at a site. An example is shown in Figure 25.

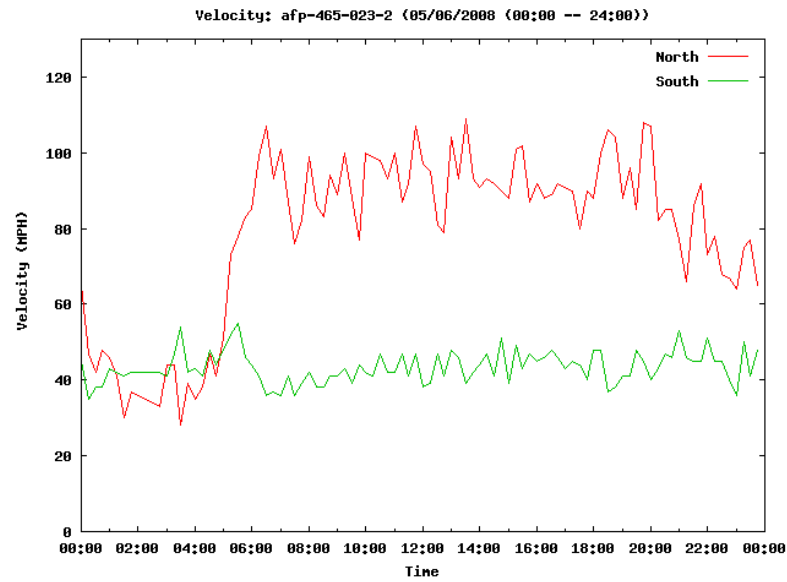


Figure 25 Velocity Graph

### 3.4.4 Velocity of each lane in one direction (vele, velw,veln,vels)

The velocities of each lane are broken into graphs by direction so that they don't become too cluttered. These graphs allow for more resolution than the velocity graphs that are averaged over each direction. This will show if one lane has an average velocity that is significantly different from the others. This is shown in Figure 26.

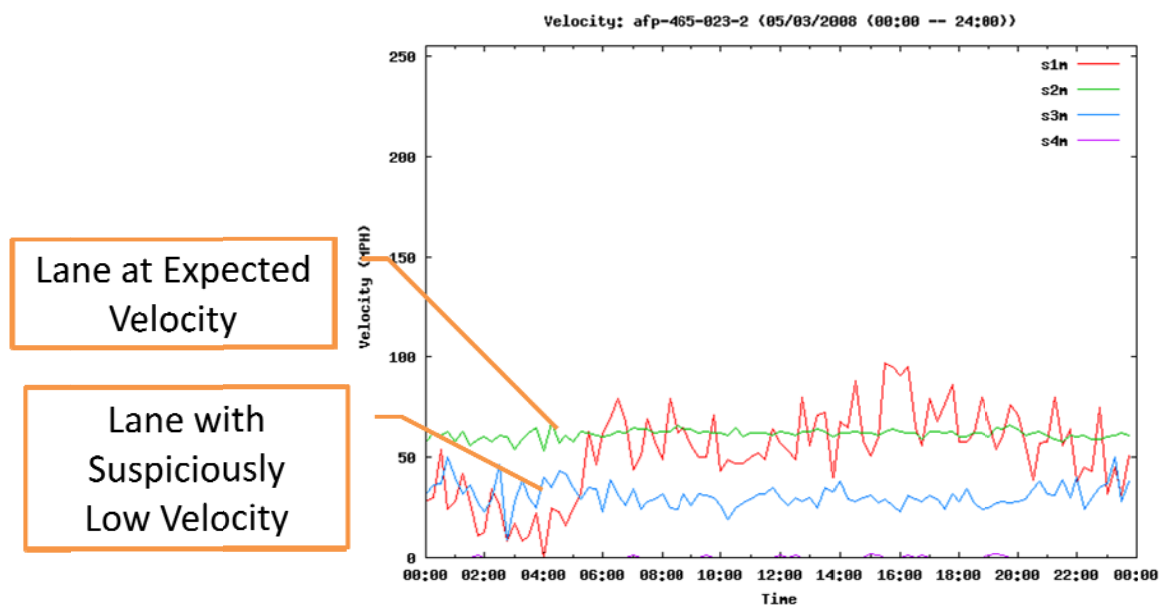


Figure 26 Average Velocity Error Example

### 3.4.5 Volume vs Time (vol) and Accumulated Volume vs. Time (volaccum)

These graphs are similar to the velocity graph except that it plots volume vs. time. Accumulated volume is also shown as an alternative way of visualizing the same information. In these graphs lead and lag volumes are shown separately. When evaluating sensor health it is important to make sure that these graphs match closely. Examples of these graphs are shown in Figure 27 and Figure 28.

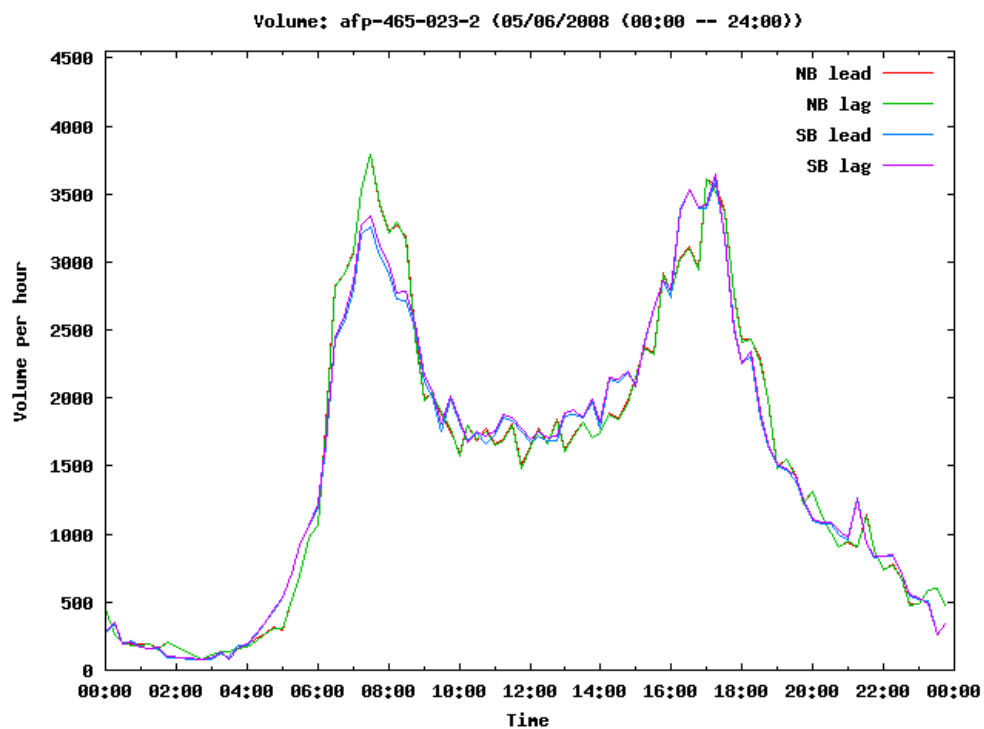


Figure 27 Volume Graph

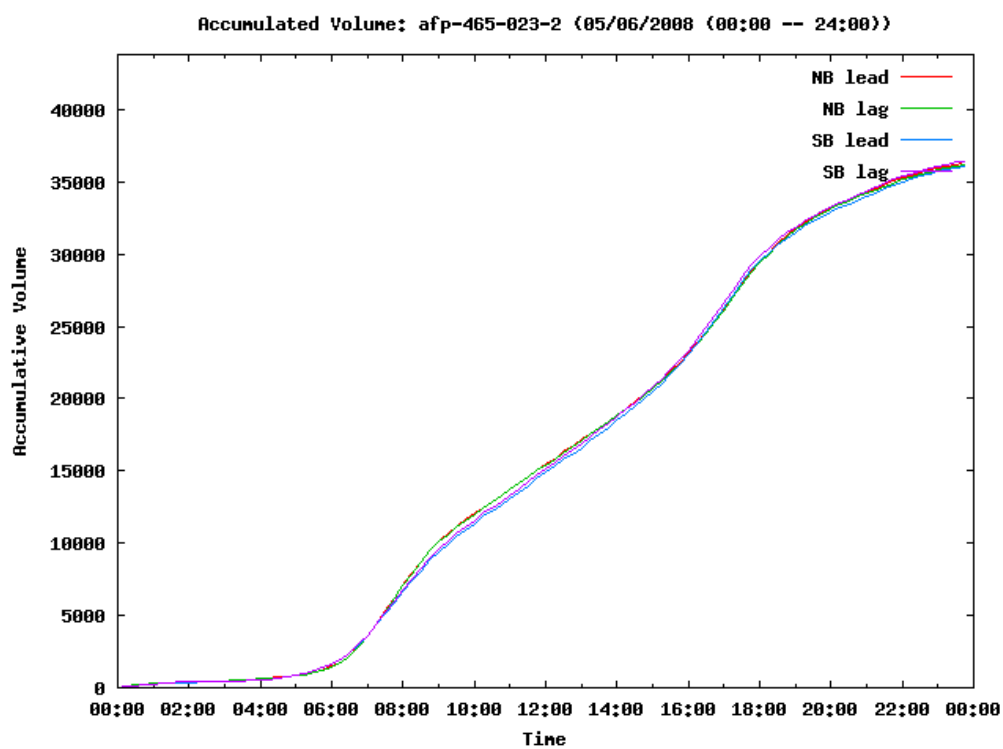


Figure 28 Accumulated Volume Graph

## 4 Results

The website prototype has already been deployed to monitor the sensor network.

Figure 29 shows how the configuration error report helped to identify small errors in configuration files.

Another example is shown in Figure 30. After reconfiguring this site, West Bound lane 2 came online. By studying the velocity curves and adjusting some configuration settings, the standard deviation of the average velocity at each site was greatly decreased. This is shown in the change between Figure 31a and Figure 30b.

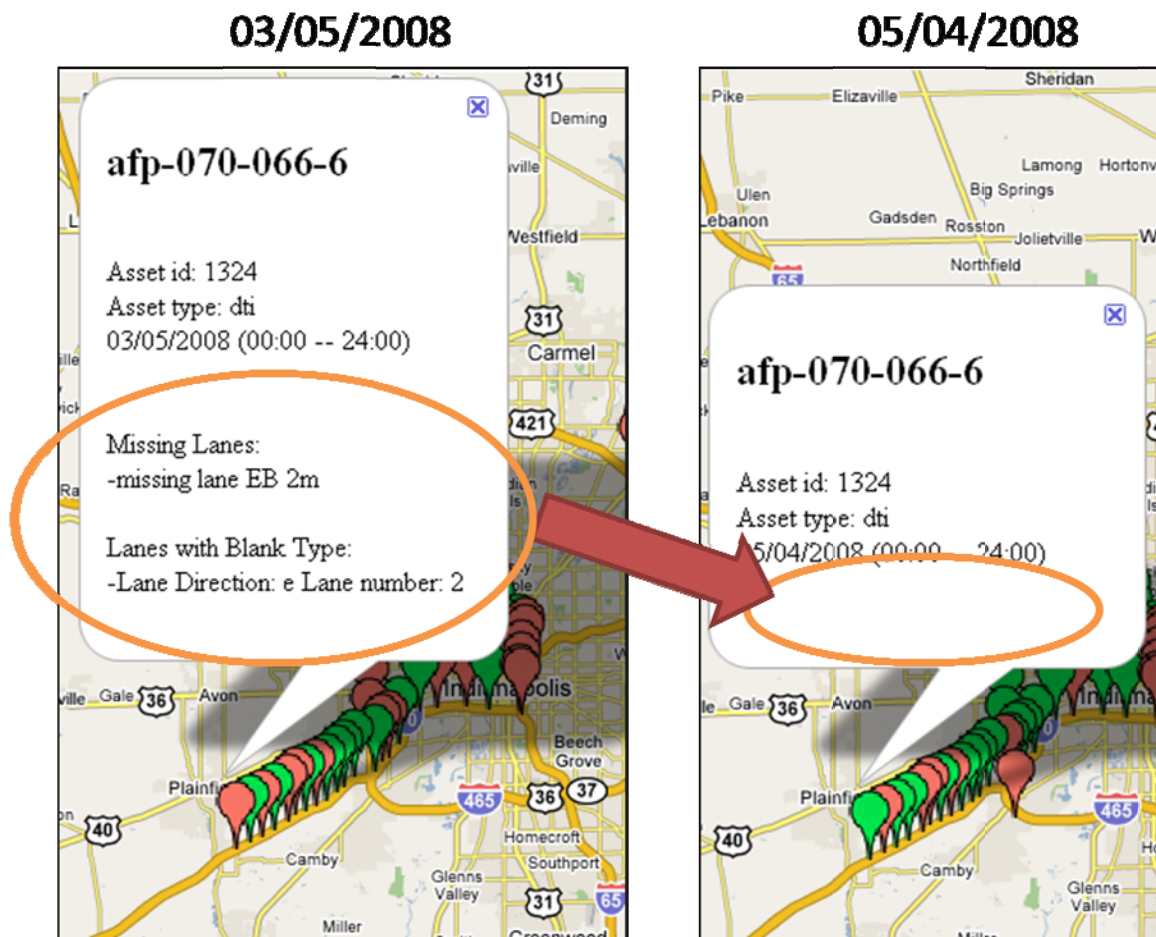


Figure 29 Example of a corrected configuration error

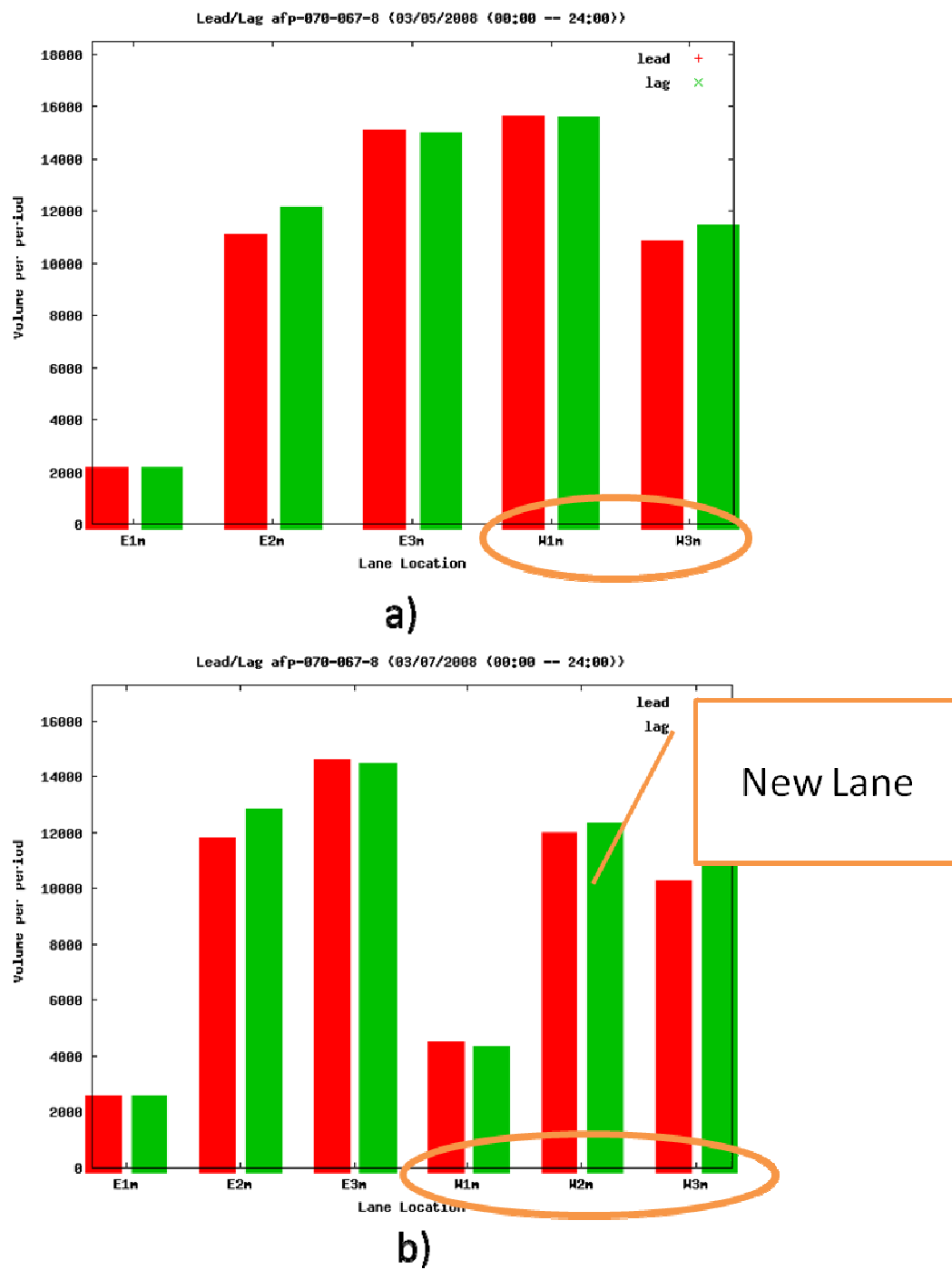
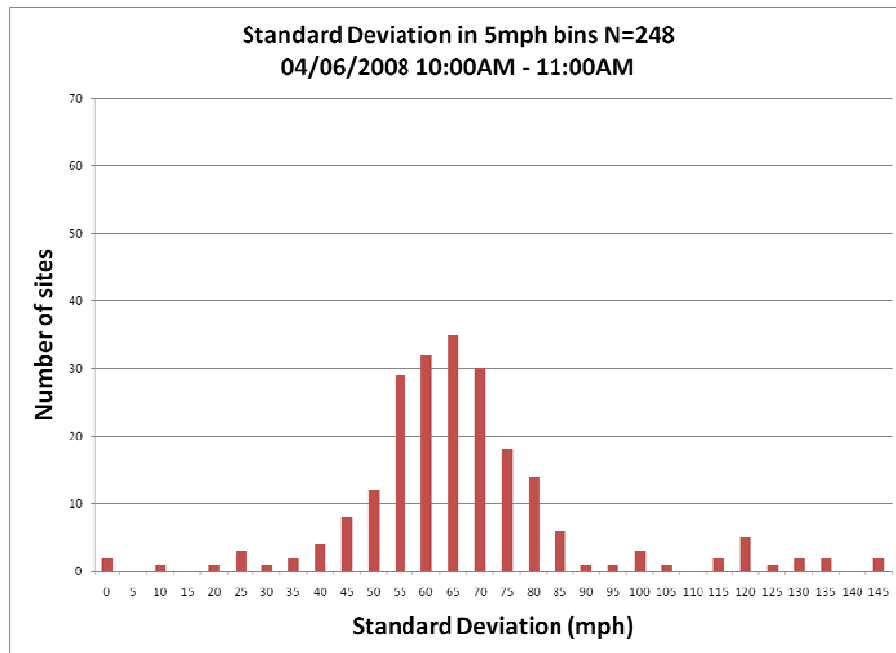
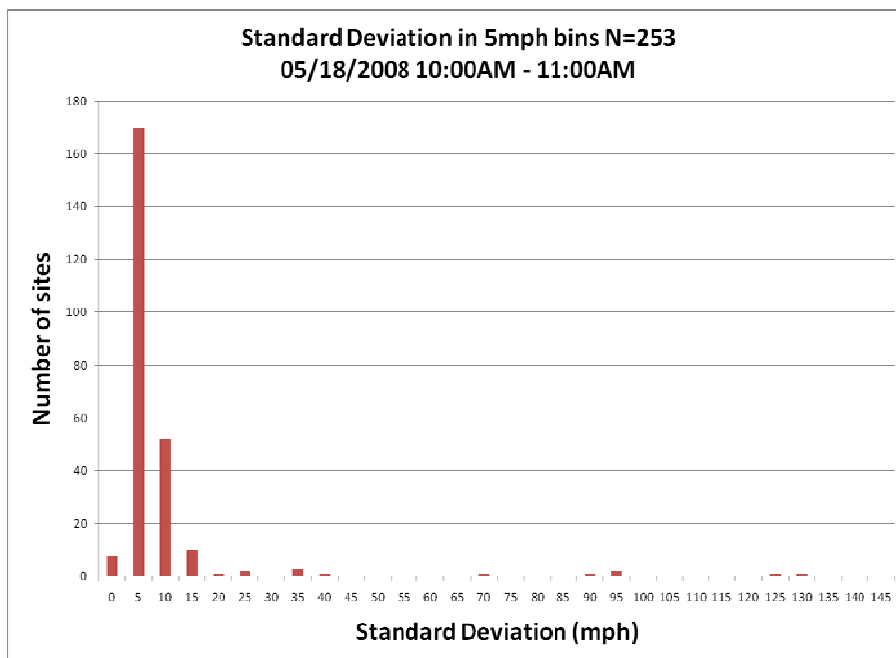


Figure 30 Additional lane appears in data set after configuration change



a) Standard deviation before reconfiguration



b) Standard deviation after reconfiguration

**Figure 31 Impact of system wide reconfiguration on standard deviation of velocities reported**



## 5 Recommendations for further work

While this prototype website has been useful, there are many other useful tools to be developed. There are several different areas where improvements can be made and other sources of information that should be investigated.

### 5.1 *Sensor Acceptance Testing*

One issue that is not addressed by the website is onsite testing at the time of installation. Quality control measurements at installation and at regular intervals are important procedures to preserve data quality. [3] It would be useful if there was a standardized mobile test that could be used on site to predict future issues.

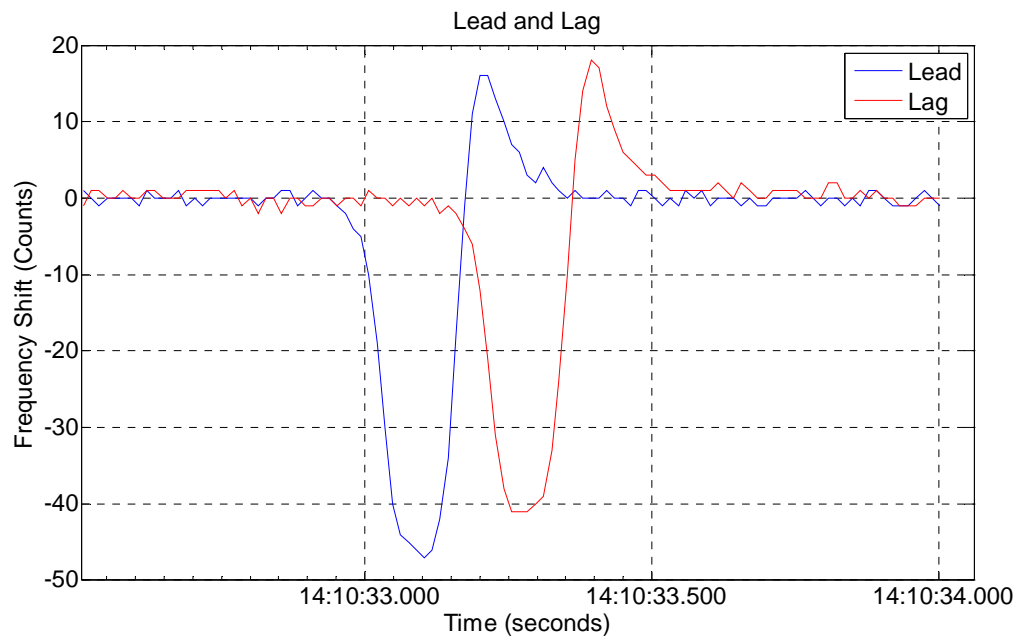
Possible metrics would include noise levels and correlation between lead and lag sensors. It is also important to optimize the scan time at each site. Access to the raw data on site can be more helpful in diagnosing problems than the summarized data that is sent back to the central database.

### 5.2 *Signature based velocity detection*

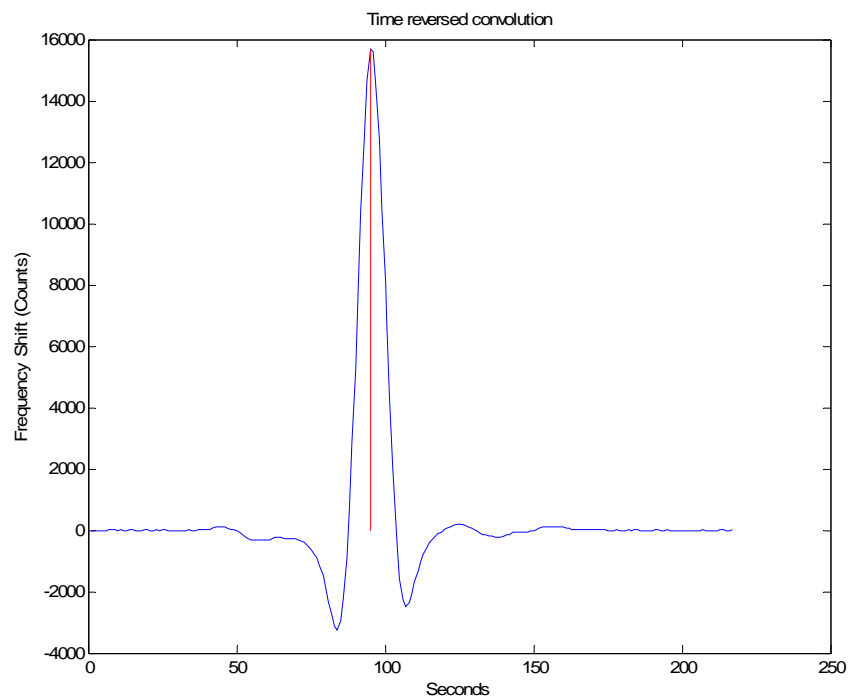
The simplest methods of calculating velocity would only use the presence output of the card and take the difference between the on times of the lead and lag sensor to calculate the speeds of the vehicles. This method is a threshold based approach. While this provides good outputs in most cases, it is prone to having outliers. It is also sensitive to the threshold chosen.

Other methods that use the raw data may be more reliable. One promising method is the correlation based method. The raw signatures are shown below in Figure 32. By taking the cross-correlation and finding the maximum, the optimal offset can be found.

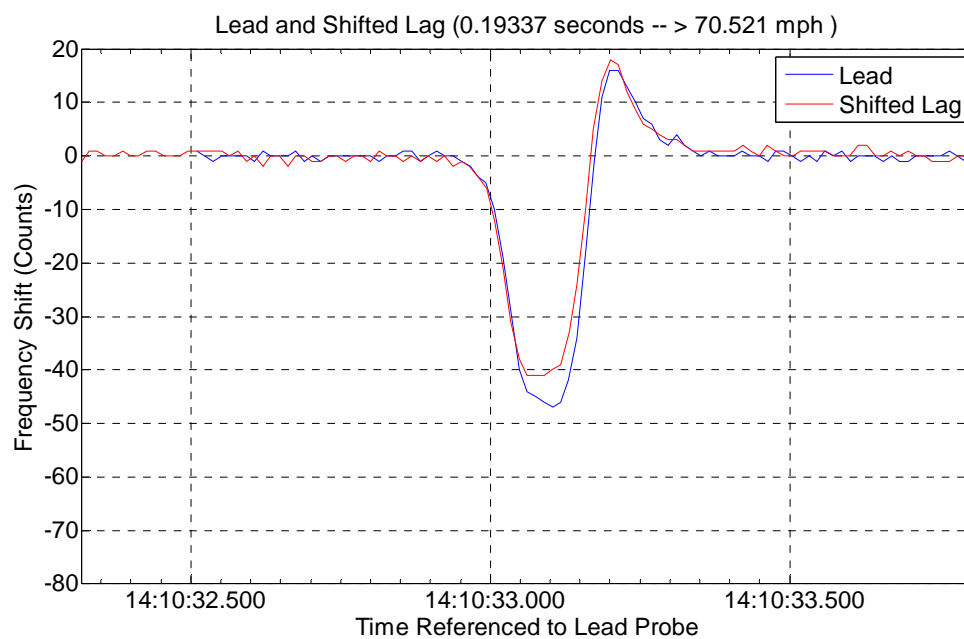
This calculation is shown in Figure 33. After shifting the lag curve by the amount calculated, the signatures line up very well. This is shown in Figure 34. Correlation is known to behave well in the presence of noise. It is also robust because no threshold needs to be chosen. Another option is to further investigate threshold algorithms to find automated ways of choosing the threshold level.



**Figure 32 Raw Lead and Lag Signatures**



**Figure 33 Cross-Correlation Maximization**



**Figure 34 Matched Signatures**

### ***5.3 Real-time Traffic Display***

The current website is only a summary of the day's events. It does not allow access to the data being currently collected. The website was designed in this way so that it only accessed the database at low impact times.

If the system were to be used for real-time monitoring, it would need to be changed so that the data was processed more regularly. It may even be beneficial to have a more interactive webpage where the user could specify the time range and type of data in order to generate a custom graph on the fly.

### ***5.4 Other Architecture Options***

The website and Google Maps design allows the information to be accessed from any internet connection. This is a great advantage in that the information is always at the closest computer, but it could be a problem if there is a desire to keep some information private. The Google Maps free license states that the website must be available to the common public. Google Maps has private licenses for its mapping tools, but these are not free.

One alternative would be to generate kml files. These Google Earth files can be loaded onto any computer and do not have the restrictions required by the Google Maps API. An archive of kml files could be made available on a password protected site. While this option is slightly less convenient, it has the advantage of maintaining privacy.

The graphing tool that was chosen is gnuplot. This free program has an extremely flexible license and does not cause any conflicts. While it has worked well for this

website, it does not have some of the features available in a database reporting tool. In order to make it easier to generate new types of reports, it may be beneficial to interface with database reporting software.

## 6 Conclusion

Reporting tools similar to the prototype developed can be incredibly useful in monitoring the sensor health in a large network as well as making the data itself more accessible. Automated configuration checks and health metrics can make it easier to debug the system by narrowing the search.

Graphical tools are a large improvement over the raw output from the database. It is important to have a multi-level view of the system so that system wide, site wide, and lane specific issues can be quickly detected and resolved.

## 7 Bibliography

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